SIGNIFICANT FEATURES FOUND IN SIMULATED TROPICAL CLIMATES USING A CLOUD RESOLVING MODEL

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1. INTRODUCTION

Cloud resolving model (CRM) has widely been used in recent years for simulations involving studies of radiative-convective systems and their role in determining the tropical regional climate. The growing popularity of CRMs usage can be credited for their inclusion of crucial and realistic features such like explicit cloud-scale dynamics, sophisticated microphysical processes, and explicit radiative-convective interaction (genuinely reviewed by Sui et al., 1994 and Tao et al., 1999, hereafter S94 and T99, respectively). For example, by using a two-dimensional cloud model with radiative-convective interaction process, Held et al. (1993), found a QBO-like (quasi-biennial oscillation) oscillation of mean zonal wind that affected the convective system. Accordingly, the model-generated rain band corresponding to convective activity propagated in the direction of the low-level zonal mean winds; however, the precipitation became "localized" (limited within a small portion of the domain) as zonal mean winds were removed. Two other CRM simulations by S94 and Grabowski et al. (1996, hereafter G96), respectively that produced distinctive quasi-equilibrium ("climate") states on both tropical water and energy, i.e., a cold/dry state in S94 and a warm/wet state in G96, have later been investigated by T99. They found that the pattern of the imposed large-scale horizontal wind and the magnitude of the imposed surface fluxes were the two crucial mechanisms in determining the tropical climate states. The warm/wet climate was found associated with prescribed strong surface winds, or with maintained strong vertical wind shears that well-organized convective systems prevailed. On the other hand, the cold/dry climate was produced due to imposed weak surface winds and weak wind shears throughout a vertically mixing process by convection.

In this study (related to Shie et al., 2000), considered as a sequel of T99, the model simulations to be presented are generally similar to those of T99 (where a detailed model setup can be found), except for a more detailed discussion along with few more simulated experiments. There are twelve major experiments chosen for presentations that are introduced in section two. Several significant feature analyses regarding the rainfall properties, CAPE (Convective Available Potential Energy), cloud-scale eddies, the stability issue, the convective system propagation, relative humidity, and the effect on the quasi-equilibrium state by the imposed constant radiation or constant surface fluxes, and etc. will be presented in the meeting. However, only three of the subjects are discussed in section three. A brief summary is concluded in the end section.

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2. SENSITIVITY EXPERIMENTS

The major characteristics of the twelve sensitivity experiments presented (all with a 25-day integration period reaching a quasi-equilibrium state) are listed in Table 1. For example, in experiment "S4M" an initial sounding of S94 ("S"), a minimum surface wind speed of 4 ms^{-1} ("4") in the bulk formulas and a mixed-wind shear condition ("M") are applied. Soundings in S94 are generally found drier aloft than that in G96. The horizontal wind profile is vertically well mixed with time by convective processes (as in S94) in the mixed-wind shear runs, while it is relaxed to its initial value in the counterpart experiments with nudging (similar to G96). Three levels of minimum surface wind speed (1 ms^{-1}, 4 ms^{-1} and 7 ms^{-1}) are applied to test their effects on climate change through produced (computed) surface fluxes. The middle value 4 ms^{-1} is picked following S94 to account for the gustiness effect in the boundary layer. Details of the characteristics of the three major components can be found in T99. The two special pairs of experiments (R4M versus R4N, and F4M versus F4N) are performed with prescribed time-invariant radiation and surface fluxes, respectively. R4M has the same set-up as S4M except that the former uses the time-averaged shortwave and longwave radiation of the latter. With radiation being kept constant, only a one-way interaction between clouds and radiation is allowed throughout the entire integration in R4M. Its purpose is to examine whether a variation (varying or constant with time) in radiation pattern would be critical in changing the cloud modeled climates. R4N is similar to R4M except that the nudging wind shear is installed. Similarly, an application of the time-averaged surface fluxes of S4M to the paired experiments F4M and F4N (throughout their integration) is intended to study whether the climate status would be altered with a change from a time-fluctuating to a time-invariant surface flux.

3. RESULTS

Only three of several major features to be presented in the meeting are discussed in the following three sub-sections, respectively. First is the characteristic of rainfall properties, followed by the CAPE feature, and the effects on quasi-equilibrium states by the variously imposed radiation and surface fluxes patterns.

Table 1: Setups for the twelve experiments conducted.

Run Name	Sounding	Minimum Wind Speed	Vertical Wind Shear	Radiation	Surface Fluxes
S1M	S94	1 ms^{-1}	Mixed	Variant	Variant
G1M	G96	1 ms^{-1}	Mixed	Variant	Variant
S4M	S94	4 ms^{-1}	Mixed	Variant	Variant
S7M	G96	7 ms^{-1}	Mixed	Variant	Variant
R4M	S94	4 ms^{-1}	Mixed	Constant	Variant
F4M	G96	4 ms^{-1}	Mixed	Variant	Constant
S1N	S94	1 ms^{-1}	Nudging	Variant	Variant
G1N	G96	1 ms^{-1}	Nudging	Variant	Variant
S4N	S94	4 ms^{-1}	Nudging	Variant	Variant
S7N	G96	7 ms^{-1}	Nudging	Variant	Variant
R4N	S94	4 ms^{-1}	Nudging	Constant	Variant
F4N	G96	4 ms^{-1}	Nudging	Variant	Constant

3.1 Rainfall Properties

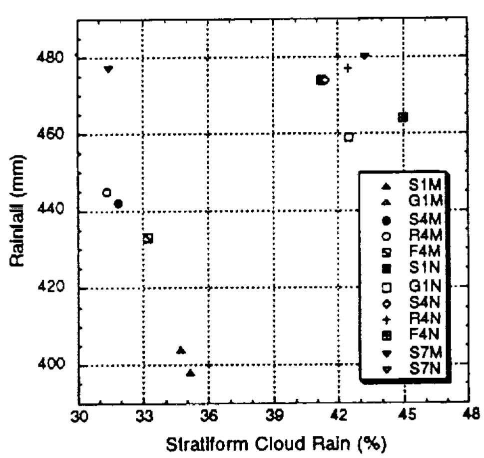

Figure 1. Scatter diagram of 25-day surface rainfall versus rainfall contribution by stratiform clouds (in %) for the twelve experiments.

Scatter diagram of 25-day surface rainfall versus the rainfall contribution by stratiform clouds (in %) for the twelve experiments is shown in Fig. 1. It first indicates that the experiments with mixed-wind shear have less rainfall contribution by stratiform clouds (between 30 to 36%), while the nudging experiments favor stratiform clouds that contribute more (between 41 to 45%) rainfall. The total rainfall intensifies with an increase in minimum surface wind for cases with mixed-wind shear whereas the contribution by stratiform clouds generally weakens. It also implies that, without the existence of a significant shear, the larger surface fluxes driven by a stronger surface wind have emerged as the dominant heat and moisture source that enhances the convective clouds as well as their contribution to the increased rainfall. On the other hand, for cases with nudging shear, they all produce large rainfall amount (with a greater role by stratiform clouds as mentioned), which however is independent of the embedded surface wind. Third, the convective clouds (55 to 70%) are still considered as the leading resource over the stratiform clouds (30 to 45%) in terms of the rainfall contribution among all the experiments.

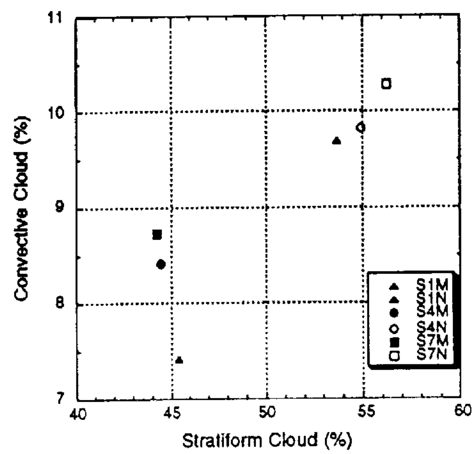

Figure 2. Scatter diagram of 25-day convective cloud coverage (in %) versus stratiform cloud coverage (in %) for three pairs of experiments.

However, the stratiform clouds dominate the cloud area coverage which is defined as a fraction of cloud region (with or without precipitation) over the entire domain, e.g., a 44.4% coverage by stratiform clouds to an 8.4% by convective clouds in S4M, a run with mixed-wind shear (see Fig. 2). This dominance by stratiform clouds elevates as the nudging shear is applied, e.g., a 54.9% coverage by stratiform clouds to a 9.8% by convective clouds in S4N. In other words, the total cloud area coverage (including both stratiform and convective clouds) enlarges by 22.5% (from 52.8% to 64.7%) due to the nudging effect. Furthermore, this cloud area enlargement due to nudging is greater with a higher minimum surface wind, i.e., a 20.1% of area increase from S1M to S1N, while a 25.7% area expansion from S7M to S7N. On the other hand, for those experiments with a mixed-wind shear, the convective cloud coverage is increased with an increased minimum surface wind (i.e., from 7.4% to 8.4%, and then 8.7%), while the stratiform cloud coverage slightly diminishes (i.e., from 45.4% to 44.4%, and then 44.2%). It again indicates that the surface latent heat flux has played a decisive role on the formation of the erect convective clouds when environment does not favor producing organized clouds; however, it does not alter the total cloud coverage which remains at about 52.8%. For the nudging cases, both the stratiform and convective clouds expand their area coverage as the minimum wind

speed increases, though the well-organized stratiform cloud dominates (53.7% to 56.2%) the convective cloud (9.7% to 10.3%) in area coverage. Apparently, the nudging wind shear performs a significant impact on the cloud system by enhancing the large-scale forcing process that generates more well-organized clouds as well as strengthening the surface flux process that generates more convective clouds.

3.2 Wet-bulb Potential Temperature & CAPE

Using the GISS GCM, Ye et al. (1998) produced a realistic linear relationship between CAPE and Θ_W in the surface layer and suggested that the CAPE variation is mostly determined by the moisture variation in the boundary layer over the tropical ocean. We found a similar linear pattern in our study using data at the end of the simulation period (Fig. 3). However, our CAPE is smaller than theirs for large Θ_W, yet larger for small Θ_W. Above all, both CAPE and Θ_W are found larger in the warm/wet cases than in the cold/dry cases that provides a consistent evidence for our finding based on a stability analysis. Accordingly, the warm/wet cases have involved in a more pseudo-adiabatic unstable environment, while the cold/dry cases have been associated with a more stable one. An additional finding from a relative humidity analysis also supports the same argument.

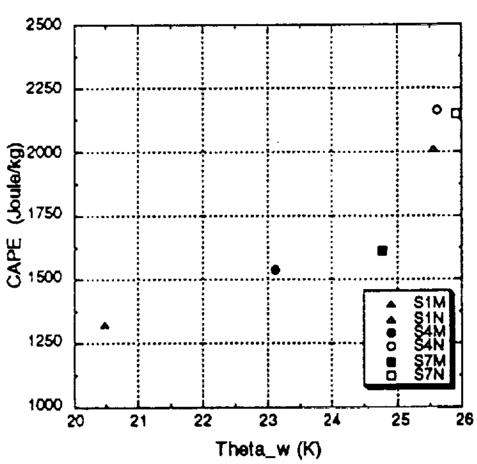

Figure 3. Scatter diagram of CAPE versus wet-bulb potential temperature at the end of simulation period for three pairs of experiments.

3.3 Constant Radiation and Surface Fluxes

In this section, whether the way (time-variant or time-invariant) radiation or surface fluxes treated in the model would be critical to alter the quasi-equilibrium state of energy and water vapor is discussed. First, by comparing R4M and S4M (or R4N and S4N), it is found that the paired experiments share the same climate regime mild/moist (or warm/wet) for the mixed-wind shear (or the nudging-wind shear) case regardless how the radiation is treated, i.e., time-variant or time-invariant (figure not shown). It implies that neither a two-way (time-variant) nor a one-way (time-invariant) radiative-convective interaction would alter a climate state, but how much the total amount of net radiation is involved could still be crucial. As a matter of fact, it is found that the equilibrium state moves up (warmer and moister) when radiation is completely shut off in our pilot runs (not shown) by considering that the net radiation would have been negative with a larger longwave cooling over a smaller shortwave heating, had them been included. Note that, the constant radiation implemented in both R4M and R4N was the time-averaged radiation obtained from S4M.

Regarding experiments associated with prescribed constant surface flux, a similar feature is found by the contrast of F4M and S4M (or, F4N and S4N). Namely, whether the surface layer interacts with the cloud system one-way (time-invariant fluxes) or two-way (time-variant fluxes) has no critical effect on the climate change. However, the surface fluxes embedded in the system are very important for the convective system to develop and reach a quasi-equilibrium state, especially for those mixed-wind shear cases while the large-scale forcing is weak. In our pilot runs excluding the surface fluxes (not shown), both temperature and water vapor are greatly reduced without reaching a quasi-equilibrium state after twenty-five days of simulation for a mixed-wind shear case. It is however found that various treatments of imposed surface fluxes more or less modify the cloud structure through the nudging effect, but not large enough to alter the quasi-equilibrium state.

4. SUMMARY

Besides the three major features discussed here, few more significant features will also be presented during the conference meeting. Even our simulations have been performed based on an environment that is more idealized than realistic, but the major features that have been found reasonable can be considered as realistically constructive. However, since the modeled quasi-equilibrium states have been found sensitive particularly to the two large-scale conditions (magnitude of the prescribed minimum wind speed and pattern of the imposed vertical wind shear), a more realistic and careful approach should be considered in our cloud-resolving model for our future research works. Further studies aiming at a better and thorough understanding of the mechanisms of the physical processes involving both the energy and water vapor budgets are also desired.

5. REFERENCES

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